Correlates of Sensitive Technologies

Mission Supporting Transformative Research

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Final Report for

Project 11-3149: Correlates of Sensitive Technologies

Preface –

For the various tasks and subtasks, we list a summary of the originally proposed intent and deliverable(s), as adapted from the initial proposal (Statement of Work), and a summary of results actually attained and deliverables submitted.

Task 1 – Leveraging Earlier Work toward Correlates of Sensitive Technologies

Subtask 1.a -

Original intent: The original intent of this subtask was to extend "existing data base(s) to incorporate variables reflecting various aspects of ENR technologies, and employment of the resulting data in the manner of Lead PI and Sprecher [CITATION: Paul Nelson and Christopher M. Sprecher, `Are sensitive technologies enablers of civil nuclear power? An empirical study,' *Atoms for Peace - An International Journal*, Vol. 3, pp. 93-112, 2010;] toward identifying such correlates." The anticipated deliverable was a "progress report outlining results as presented in more detail in article intended for conference proceedings."

Actual accomplishments: The data base, and a model employing it, were described in the MS thesis of Mr. Nischal Kafle (Kafle, Nischal (2014), "Statewise Correlates of Civil Nuclear Energy," Master's thesis, Texas A & M University, Nuclear Engineering, available electronically from http: / /hdl .handle .net /1969 .1 /153366). A copy of this thesis was submitted to NEUP as part of the quarterly report for Quarter 3 of FY 2014. This thesis constitutes the deliverable for Subtask 1.a.

Subtask 1.b -

Original intent: Addition to data base of estimates of latency times for acquisition of various forms of ENR capabilities, and outline of conceptual model employing latency as dependent variable. The deliverable proposed was a "progress report outlining results as detailed in manuscript intended for journal publication."

Actual accomplishments: Three separate items were uploaded to PICSNE, with the report for Quarter 1 of FY 2014, as the deliverable for this subtask: "COST ENR Dataset 2013-1209.xlsx ," "Nuclear Latency Dataset Codebook.docx," and "Data Description 2013-1217." A journal article based on these documents has now been published: Fuhrmann, Matthew and Benjamin Tkach. 2015. "Almost Nuclear: Introducing the Nuclear Latency Dataset." *Conflict Management and*

Peace Science **32** (4): 443-461. All of the files associated with the Nuclear Latency dataset have been posted at http://www.matthewfuhrmann.com/datasets.html.

Subtask 1.c-

<u>Original intent</u>: Development and description of a taxonomy of nodes occupied by sensitive technologies along the various pathways to proliferation. The anticipated deliverable was "a progress report outlining the taxonomy as described in a Laboratory report."

<u>Actual accomplishment</u>:   The deliverable for this subtask was submitted as the letter report "Correlates of Sensitive Technologies – Subtask 1.C Deliverable Report**"** (file name "COST Subtask 1c.pdf") with the report for Quarter 2 of FY 2015.

Task 2 – *Amalgamated data base*

 <u>Original intent</u>: The original intent was to develop "… a single amalgamated database that is expressly designed to address the issue of what state properties are best correlates of sensitive technologies ."

<u>Actual accomplishments</u>:

Given the dissimilarities between data set, development of a report that addresses questions about the utility of Quantitative Empirical Analysis (of factors possibly contributing to proliferation) was judged to provide more value? The final deliverable for this task was thus a paper published in the proceedings of the INMM 56th Annual Meeting (July 12-16, 2015, Indian Wells, CA, copy herewith attached (CITATION: Meyappan Subbaiah and Paul Nelson, "The Role of Quantitative Empirical Analysis in Identifying and Reducing Proliferation Risk"**)** as the deliverable for this task. The paper was presented at the INMM meeting, in poster format, by Mr. Meyappan Subbaiah. This work also was presented, along with subsequent related developments at PNNL, to the Winter 2015 American Nuclear Society - Nuclear Nonproliferation Policy Division General Panel (G. A. Coles, "Perspectives on Proliferation Risk Assessment," November 8-12, 2015 ANS Winter Meeting and Expo., Washington D.C.)

Task 3 – *Model developments*

Subtask 3.a:

<u>Original intent</u>: Development of quantitative empirical model for acquisition of ENR technologies (and possibly other sensitive technologies), with corrections for problems associated with TSCS analysis. The indicated deliverable was a "progress report describing details of model."

Actual accomplishment:

The manuscript "A Spatial Model of Nuclear Technology Diffusion," by Matthew Fuhrmann and Benjamin Tkach, was uploaded (as file Fuhrmann Tkach 2015-0608.pdf) to PICSNE as part of the submission of the progress report for Quarter 4 of FY 2015 (Y2015Q4.pdf). This document is intended as the final deliverable for Subtask 3.a, although it is intended for ultimate publication in the open literature, and therefore may be subject to further revision, pending peer review. This manuscript documents, among other matters, the Nuclear Latency dataset mentioned under Subtask 1.b above, and provided by TAMU Political Science to PNNL as the basis for the capstone Subtask 3.b described below.

Subtask 3.b:

Original intent: The indicated activity was "development of (an) expert-judgment model. The proposed deliverable was a "detailed progress report."

Actual accomplishments:

During the summer of 2015 Mr. Meyappan Subbaiah, Texas A&M (TAMU) Masters of Science in Nuclear Engineering student, served as an intern to the DOE National Security Internship Program (NSIP) program to perform modeling associated with Task 3.b. Under principal support from the PNNL subcontract for this project, Mr. Subbaiah worked with PNNL domain and modeling experts to develop a model to demonstrate the value of Bayesian Networks in exploring indicators of proliferation (specifically development of sensitive technologies) using expert judgement and data. The variables explored and associated dataset in this work were taken from the results of Subtask 3.a, as described above.

This culminating task of the project is described in a PNNL draft report, tentative title "Predictive Model Using Correlates of Sensitive Technologies and Expert Judgement." A copy of this report (dated September 30, 2015) was submitted by PNNL, to TAMU. A copy of this draft report was uploaded (on 10/22/15, file name COST Task 3b Draft Report_30Sept2015_Final_signed.pdf to PICSNE as part of submission of the quarterly report for Quarter 4 of FY2015. A four-month no-cost extension of the project was requested and authorized, for the principal purpose of modifying this report into a more finished deliverable. The ultimate product is intended to be the M.S. thesis of Mr. Meyappan Subbaiah; work on that thesis will continue beyond the current project, on the basis of support from other sources. A copy of the proposal for that thesis, "An Analysis on the Correlates of Nuclear Proliferation and Nuclear Energy" is appended to this final report. Some of the expert elicitation associated to this subtask was conducted with PNNL staff, during the term of the no-cost extension cited above.

Task 4 – *Correlates of Sensitive Technologies: Model Application*

Original intent: Exploration and comparison of results of the models of Subtasks 3.a and 3.b as applied to (at least) one significant policy issue. Progress report detailing results as described in detail in one or more accompanying manuscripts intended to be submitted for possible journal publication. As a result of budgetary reductions, in the final proposal this task was downgraded to status of "as project resources permit."

Actual accomplishment: With due consideration of the challenges afforded by the funded tasks, project resources did not permit this task to be addressed.

THE ROLE OF QUANTITATIVE EMPIRICAL ANALYSIS IN IDENTIFYING AND REDUCING PROLIFERATION RISK

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ABSTRACT
By "Quantitative Empirical Analysis" (QEA) is intended the use of statistical methods to infer, from data that often tend to be of a historical nature, the characteristics of states that correlate with some designated dependent variable (e.g. proliferation of nuclear weapons). QEA is a well-established approach in the social sciences, but is not notably well-known among physical scientists, who tend to think of the social sciences as inherently qualitative. This article attempts to provide a snapshot of research, most of which has evolved over the past decade, involving the application of QEA to issues in which the dependent variable of interest is intended as some measure of nuclear proliferation. Standard practices in QEA are described, especially as they relate to data collection. The QEA approach is compared and contrasted to other quantitative approaches to studying proliferation-related issues, including a "figure of merit" approach that has largely been developed within the DOE complex, and two distinct methodologies termed in a recent US National Academy of Sciences study as "case by case" and "predefined framework." Sample results from QEA applied to proliferation are indicated, as are doubts about such quantitative approaches. A simplistic decision-theoretic model of the optimal time for the international community to intervene in a possible proliferation scenario is used to illustrate the possibility of synergies between different approaches.

INTRODUCTION
The objective of this note is to provide an overview of application of "quantitative empirical analysis" (usually abbreviated as "QEA") to proliferation-related issues. Its intended audience is primarily physical scientists and engineers who have interest in preventing proliferation of nuclear weapons, but are not familiar with QEA as an open-source approach to understanding issues related to such proliferation. By QEA here is intended the approach to the social sciences, particularly the International Relations (IR) subfield of political science, that is based on the statistical analysis of quantitative data; see, e.g., [1]. This approach is grounded in the philosophical tradition of positivism, which most often is traced back to [2]. As applied to political science the objective typically is to infer, from historical data, the characteristics of states that correlate with some designated dependent variable (e.g. some measure of the proliferation of nuclear weapons). An early example of the application of QEA to a question from the science of U.S. domestic politics is [3]; likewise [4] is a representative early example from IR. Montgomery and Sagan [5] identify two

"waves" of application of QEA to nuclear proliferation. They suggest Kegley [6] and Meyer [7] as representative of the first wave, and Singh and Way [8] as perhaps the initial instance of the second wave. Such applications have evolved into a very active subfield of academic IR research [9]. QEA is thus distinct from other quantitative methodologies for addressing various aspects of nuclear proliferation, such as the figure of merit developed by Bathke and collaborators (e.g., [10]), and the various methodologies collectively referred to in a recent US National Academy of Sciences study [11], henceforth "NAS Study," as "case by case" and "predefined framework."

The present work focuses on the question of what, if anything, QEA might provide by way of information useful to those responsible for policy decisions related to (non)proliferation of nuclear weapons. It begins with a section on the distinction between proliferation resistance and proliferation risk. Then follows a section in which standard practices in QEA are briefly described, with some emphasis on the tradition of open-sourcing data, and on various publicly accessible data bases, particularly those potentially bearing on questions of nuclear proliferation. The various quantitative approaches to proliferation issues mentioned above are then compared and contrasted, especially in the context of proliferation resistance, proliferation risk, and relations between the two.

Sample results from QEA applied to proliferation are indicated, and general doubts about such quantitative approaches are briefly reviewed. An example of a result is the observation [12] that several related works in QEA collectively suggest the beneficial impact that "nuclear weapons do not affect the frequency of conflict, but they do affect the timing, duration, severity, and outcome of conflict." An example of a doubt is the skepticism of Montgomery and Sagan [5] toward the predictive value that QEA models bring to the study of nuclear proliferation. A simple decision-theoretic model for the optimal time for the international community to intervene in a possible proliferation scenario is employed to illustrate possible synergies between QEA and other methodologies for studying proliferation-related issues. Conclusions stemming from the present work are briefly summarized.

PROLIFERATION RESISTANCE AND PROLIFERATION RISK
Proliferation risk sometimes (e.g., [11], [13]) is expressed as

$$R = \sum_{\alpha} L_{\alpha} S_{\alpha} C_{\alpha}, \tag{1}$$

where α indexes technological pathways to proliferation, L_{α} is the probability that the state of interest will attempt to proliferate along pathway α, S_{α} is the probability that such an attempt will be successful, C_{α} is the consequences of such success, and the sum is over all pathways. This definition of proliferation risk has in common with the traditional definition of "risk" in nuclear safety that both are expected values of the consequences of some adverse event.

Eq. (1) is questionable quantitatively (e.g., what is the nature of a "consequence" that justifies adding consequences along the individual pathways to obtain a total consequence). Nonetheless, qualitatively the product $R_{\alpha} = L_{\alpha} S_{\alpha} C_{\alpha}$ clearly is the expected value of the consequences of proliferation along the particular pathway α, regardless of the nature of those consequences.

Therefore, each of the factors in this product somehow contributes directly to the proliferation risk associated to that pathway.

Much has been made of qualitative definitions of *proliferation resistance*. For example, proliferation resistance has been defined [14] as "the characteristic of a Nuclear Energy System (NES) that impedes the diversion or undeclared production of nuclear material or misuse of technology by states seeking to acquire nuclear weapons or other nuclear explosive devices." But it seems intuitive that any such definition should have the property that the proliferation *resistance* associated to a particular pathway α is determined by, and varies inversely with, S_α = probability of successful proliferation along pathway α. But of course the proliferation *risk* associated to that pathway, $R_\alpha = L_\alpha S_\alpha C_\alpha$, depends as well on L_α = probability that pathway will be chosen for proliferation, and its associated consequences; the former in particular can depend on the proliferation resistance of that pathway (i.e., on S_α). This is simply one perspective of many as to why "proliferation risk" is a broader, more encompassing, term than is "proliferation resistance."

STANDARD PRACTICES IN QEA
As defined earlier, QEA is the use of statistical and mathematical methods to analyze characteristics of states that are connected to a specific designated dependent variable. For present purposes study, the designated dependent variable is some quantity deemed to be related to the proliferation of nuclear weapons.

As regards statistical or mathematical modeling there seems to be little that is used in QEA that is not reasonably familiar to physical scientists and engineers, especially those who work in or around issues that require some elements of statistical analysis of empirical data. This would include, for example, any form of risk analysis, as applied to fields such as reliability, nuclear safety or nuclear safeguards. It is perhaps worth mentioning that STATA [15] seems to have been the statistical modeling engine historically predominantly used in QEA,[a] as that software package seems less used in the physical sciences. The Wikipedia article on Stata [16] describes it as "a general purpose statistical software package" most of whose "users work in research, especially in the fields of economics, sociology, political science, biomedicine and epidemiology."

What does tend to be relatively unknown among physical scientists and engineers is the extensive amount of open-source data that has been collected by the academic IR community, and made freely available. Here we point to a few illustrative examples of such datasets. For this purpose it is convenient to separate such data sets conceptually into two classes: *i)* General purpose IR data sets that arguably have relevance to a national tendency to proliferate; and *ii)* data sets that have been assembled for the specific purpose of studying some issue deemed to be related to proliferation of nuclear weapons.

Two prime class *i)* examples are the *Polity IV* [17] and the various data sets of the Correlates of War (COW) project [18]. Here "polity" is used generically in the sense of the dictionary definition [19] of "a form of government," although variants of that term also are used within the Polity IV data set

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[a] In recent years the R software environment [34] seems to be coming into increasing favor for QEA.

to refer to various particular variables whose values are encoded (i.e., captured, reported) within the data set. For example, the *POLITY IV* data sets, which are available through [17] in both Excel and SPSS formats, among other data contain annual values, from 1800, of the "polity" values for the governments of over 160 states, on a standard scale ranging from -10 (strongly autocratic) to +10 (strongly democratic). The *Polity IV* project users' manual [20] (also accessible through [17]) contains guidelines for encoding the various governmental attributes from which values of polity, among other encoded variables, are obtained. Somewhat interestingly this manual contains the caution that the procedure used to fold more fundamental index values measuring democratic and authoritarian tendencies individually into a unitary polity scale "in many ways runs contrary to the original theory," circa 1975, underlying the Polity IV data set, and its forebears. On the other hand, this caution also can be viewed as an illustration of the exemplary tendency to document process in a manner that in principal promotes the ability to identify sources of differing results.

The COW Project classifies an armed conflict as a war or a "Militarized Interstate Dispute" (MID) according respectively as it causes at least or fewer than 1000 fatalities. Data sets characterizing such incidents are available through the web site of the COW Project [18]. As an example of the type of information available, the MID codebook [21], which also is accessible through [18], indicates (in much more detail),variables encoded in the MID dataset (accessible from [18]) that reflect identifying information, temporal extent, severity, participants and outcome of such disputes. The MID dataset, Version 4.01, contains data pertaining to nearly 2600 MIDs that occurred between 1816 and 2010. The article of record for this version is [22]; in particular this article describes the coding rules employed. There also exist data sets under the COW project that relate to wars, as defined above. "The COW Project introduced COW Wars v4.0, 1816-2007 in 2010" [18], apparently originally only for "wars that involved the government of a member of the interstate system (a state) in one form or another" [18]. Subsequent efforts included data for nonstate wars, following the typology for wars introduced in [23], and subsequently refined in [24]. This extension seemingly could be very helpful to understanding the era of asymmetric warfare that many see the world as now entering.

Aside from such widely used generic datasets, data also are widely synthesized for the purposes of studies employing QEA to study various specific issues. For example, Figure 1 shows a representative example of the dataset employed in [25] to study the hypothesis that "Countries with former rebels as heads of state are more likely than states with nonrebel leaders, on average, to pursue nuclear weapons programs." A publicly accessible link to the dataset used for this study exists at [26]. The data file was created in the .dta format native to Stata, but in Figure 1 has been converted to an Excel spreadsheet. The rows are organized so as to facilitate the use of either leader or state-year as the unit of analysis. The columns having names that are not more-or-less self-evident are associated to variables as follows [25]:

- *ccode*: A unique country identifier from the Correlates of War project
- *pursuit*: "A dichotomous variable … coded 1 if a leader is actively trying to build nuclear weapons in year *t* and 0 if not."
- *rebel*: "… a dichotomous variable that is coded 1 if a leader participated in activities designed to overthrow the government of a state prior to coming into office and 0 otherwise.
- *milservice*: military service, coded as a dichotomous variable;

- *fiveyear*: "… coded 1 if a country has been involved in a civil war in the last five years and 0 otherwise."
- *spally*: "… a variable measuring whether a state has a defense pact with a superpower that possesses nuclear weapons."
- *nonbombyrs*: Number of years passed without launching a nuclear weapons program [27].
- *revbkgnd_alt*: An alternate measure of a leader's revolutionary background, used to check for robustness [27].

Janpuangtong and Shell [28] have applied methods of artificial intelligence to automated searching for data relevant not to proliferation, but to the kindred question of understanding the motivation states have for pursuing civil nuclear energy. This line of research seems promising as a means for avoiding the necessity of subject matter expertise in assessing proliferation risk.

	A	C	E	F	K	P	Q	R	X	Y	AC	AD	AF	BH	BX
1	ccode	year	leadername	startdate	enddate	entry	exit	pursuit	rebel	milservice	fiveyear	polity2	spally	nonbombyrs	revbkgnd_alt
7603	750	1960	Nehru	15-Aug-47	27-May-64	Regular	Natural Death	0	1	0	1	9	0	13	1
7604	750	1961	Nehru	15-Aug-47	27-May-64	Regular	Natural Death	0	1	0	1	9	0	14	1
7605	750	1962	Nehru	15-Aug-47	27-May-64	Regular	Natural Death	0	1	0	1	9	0	15	1
7606	750	1963	Nehru	15-Aug-47	27-May-64	Regular	Natural Death	0	1	0	1	9	0	16	1
7607	750	1964	Nehru	15-Aug-47	27-May-64	Regular	Natural Death	0	1	0	1	9	0	17	1
7608	750	1964	Nanda	27-May-64	9-Jun-64	Regular	Regular	0	1	0	1	9	0	0	1
7609	750	1964	Shastri	9-Jun-64	11-Jan-66	Regular	Natural Death	1	1	0	1	9	0	0	1
7610	750	1965	Shastri	9-Jun-64	11-Jan-66	Regular	Natural Death	1	1	0	1	9	0	0	1
7611	750	1966	Shastri	9-Jun-64	11-Jan-66	Regular	Natural Death	1	1	0	1	9	0	0	1
7612	750	1966	Nanda	11-Jan-66	24-Jan-66	Regular	Regular	1	1	0	1	9	0	0	1
7613	750	1966	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	1	0	0	1	9	0	0	1
7614	750	1967	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	1	9	0	0	1
7615	750	1968	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	1	9	0	1	1
7616	750	1969	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	1	9	0	2	1
7617	750	1970	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	1	9	0	3	1
7618	750	1971	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	1	9	0	4	1
7619	750	1972	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	1	0	0	1	9	0	5	1
7620	750	1973	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	1	0	0	1	9	0	0	1
7621	750	1974	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	1	0	0	1	9	0	0	1
7622	750	1975	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	1	0	0	1	7	0	0	1
7623	750	1976	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	1	7	0	0	1
7624	750	1977	Gandhi, I.	24-Jan-66	22-Mar-77	Regular	Regular	0	0	0	0	8	0	1	1
7625	750	1977	Desai	24-Mar-77	15-Jun-79	Regular	Regular	0	1	0	0	8	0	0	1

Figure 1- Sample segment of the dataset underlying [25]

COMPARISON TO OTHER APPROACHES TO ANALYSIS OF PROLIFERATION

Recall from the second paragraph of the Introduction the stated purpose here to focus on what "QEA might provide by way of information useful to those responsible for policy decisions related to proliferation of nuclear weapons." The principal objective of this section is to establish that focus, and somewhat sharpen it... First we wish to expand upon this point, so as to encompass methodologies other than QEA. Second, we wish to identify, from the NAS Study, the types of questions likely to be of interest to decision makers. Third, we wish to build upon the three-factor formula (1) to establish a framework that might be useful for thinking about the relationship between different methodologies and the types of information needed by decision makers.

The NAS Study acknowledges the existence and use of QEA, but aggregates it with more traditional qualitative approaches as a "political science methodology". Here we disaggregate the two, and term the latter as "qualitative political science." Additionally the NAS study calls out

what it terms as the "case by case" and "predefined framework" methods for proliferation risk assessment.[b] Be that as it may, the focus here is on understanding the differences between these three different types of approaches, from the perspective provided by the three-factor characterization (1) of proliferation risk.

The following quotations from the NAS Study are extremely helpful in understanding the types of information desired by decision makers. Task 1 of that Study (p. 19) reads as:

> **TASK 1: Identify key proliferation policy questions capable of being answered by a technical assessment of the host-state proliferation risk posed by a given nuclear fuel cycle, and discuss the utility of these questions for informing international nonproliferation policy decisions.**

Further, on pp. 20 and 21, one finds:

> "Decisions to enter into … 123 agreements require a Nuclear Proliferation Assessment Statement … as part of this process. … Analysis to inform the process would be done on a case-by-case basis tailored to the particular country in question and would synthesize information about technical capabilities, political motives, past behaviors, as well as overall analysis of the regional security situation. Of all of these factors, *host-state motivation is perhaps the most difficult to assess because it ultimately depends on the subjective decision making of political leaders*." (Italics added)

The finding associated to Task 1 in the NAS study is:

> FINDING 1.1: Technical assessments related to aspects of proliferation risk do make valuable contributions to nonproliferation policy decisions on a broad range of topics such as peaceful international nuclear cooperation, export control, nuclear fuel cycle R&D, and nuclear safeguards. However, technical assessments do not fully answer nonproliferation policy questions. Final decisions also include consideration of a much broader set of political, security, economic, and cultural issues.

This certainly seems an adequately nuanced conclusion. Nonetheless, here we suggest use of (a modest expansion upon) the three-factor formula (1) for proliferation to provide a unified framework for assessing the capability of the various methodologies to provide information relative to all of these issues, technical and otherwise.

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[b] The NAS Study [11, p. 1] characterized a "predefined framework" as a methodology that "typically divides the nuclear fuel cycle into processing steps, assigns values to intrinsic (material- and fuel cycle-specific technical details) and extrinsic (safeguards, inspections, and facility operational details) proliferation barriers at each step, combines the results using weighting functions, and determines the overall proliferation resistance of fuel cycle options using a predefined approach." It contrasted such approaches to the more common "case-by-case" assessments that use "multidisciplinary teams of experts to address technical topics as they arise."

Specifically, let $L_\alpha = P_0 \Lambda_\alpha$, where P_0 is the probability that the subject state chooses to proliferate, and Λ_α is the probability that it will elect to proliferate along pathway α, given that it chooses to proliferate. Then the risk of proliferation along pathway α is

$$R_\alpha = P_0 \Lambda_\alpha S_\alpha C_\alpha. \tag{2}$$

Table 1 indicates our assessment of the ability of each of the methodologies listed above to assist in evaluation of the four different factors in (2). Here the coding is as follows:

y = yes, methodology likely to provide an assessment;

m = maybe, methodology might be able to provide an assessment;

n = no, methodology unlikely to provide an assessment.

Table 1- Capabilities of the four methodologies to account for the four factors in the risk, as given by (2)

model type↓\factor→	P_0	Λ	S	C
QEA	Y	M	M	N
Predefined Framework	N	M	Y	N
Case-by-Case	N	M	Y	M
Qualitative Political Science	Y	N	N	Y

Two comments need be made about Table 1. First, the evaluations necessarily invoke some assumptions about the body carrying out the process associated to the model. For example, for the case-by-case models we assume the experts whose opinions are sought have exclusively technological expertise. Second, the *ad hoc* list of model (theory) types in Table 1 can be considerably expanded; see [29], and the various papers in the special journal issue that it introduces, for a substantial number of additional candidates.

QEA: RESULTS AND DOUBTS
This section begins with a review of the conclusion of three typical applications of QEA to nonproliferation issues. Methodological and motivational matters are not given their truly warranted attention, in order to provide the widest possible attention to the nature of the conclusions that are capable of being drawn from QEA. The section concludes with a discussion of doubts that have been expressed about the utility of QEA, especially in the context of nuclear proliferation.

Singh and Way [8] was already briefly described in the Introduction. Much of the discussion in this paper was motivational in nature, as to why quantitative studies might have advantages over more traditional qualitative approaches (e.g., comparative case studies). This work does not follow the customary statistical path of exploring some group of specified hypotheses. Rather it considers the problem of estimating the hazard rate for proliferation, by a specified state, in terms of various independent variables considered as representing technological, external, or domestic determinants of proliferation.

Through the prism of this estimated hazard rate, Singh and Way then identify some "countries that had a high predicted hazard for several years, yet never (to the best of our knowledge) seriously explored the nuclear option." With some selectivity for subsequent events, these include Saudi Arabia, Syria and Egypt. Somewhat similarly, entries on a shorter list of states "who sought nuclear weapons but should not have" (for various reasons) include Libya, Brazil, Algeria, and Pakistan. A perhaps provocative conclusion is:

> *... that actions aimed at the following would reduce a country's temptation to pursue nuclear arms: reduce the threat posed by its external environment, accelerate economic growth so that it moves well beyond the threshold of temptation and onto the decreasing hazard portion of the relationship between development and risks of proliferation, encourage integration into the world economy, and encourage a defensive alliance with a great power. Arguably, current American policies toward proliferators have exactly the opposite effects. In the context of our model, they would probably result in an increasing predicted hazard rate* (for proliferation).

As previously mentioned, Fuhrmann and Horowitz [25] used the QEA methodology to study the hypothesis that "countries with former rebels as heads of state are more likely than states with nonrebel leaders, on average, to pursue nuclear weapons programs." They concluded that although:

> *... most theories of international relations and existing research on nuclear proliferation suggest it does not matter who actually leads a given nation-state when it comes to nuclear proliferation dynamics, we show, in contrast, that leaders with prior rebel backgrounds are particularly likely to pursue nuclear weapons. Having participated in a struggle for independence against a foreign power or a rebellion against the government, former rebels are particularly likely to seek absolute national security in the form of nuclear weapons. Seeing nuclear weapons as invasion insurance and fearing the loss of sovereignty, former rebels are much more likely to pursue the bomb than otherwise similarly situated leaders. We show that this result does not just emerge from leaders in autocratic regimes or those that take power after civil wars.*

Here we note in particular the contrast between the empirical confirmation of such a trend among national leaders, and the observation from the NAS study that "host-state motivation is ... difficult to assess *because it ultimately depends on the subjective decision making of political leaders.*"

Montgomery and Sagan ([5], pp. 302-304) cite "five serious problems that have ... plagued ... quantitative studies of nuclear proliferation": *i)* inherent difficulty in "accurate coding of the dependent variables," coupled with the allegation that "findings are rarely subjected to sufficient robustness tests using alternative codings"; *ii)* "problematic coding rules for independent variables," including the observation that "important factors that have been discussed in historical case studies of proliferation – such as leaders' psychology, bureaucratic power, and military autonomy and the desire for prestige – are often excluded altogether or measured poorly in statistical studies"; *iii)* lack of tight coupling between the empirical questions being investigated and

the methodologies and datasets employed; *iv)* a perceived failure to produce insights that add significantly to our understanding of proliferation; and *v)* a tendency for statistical findings to "ignore or gloss over individual data points that are crucially important for policy making and wider scholarly debates." The authors note (p. 322) that what they perceives as a second wave in "the quantitative study of proliferation is a welcome advancement" because "some of the questions and debates in this subfield can only be fully tested when using statistical methods." Nonetheless, in keeping with the discussion surrounding Table 1 above, they note that other questions and debates "will require mixed methods, combining historical case studies, deductive reasoning, and quantitative research." They note "some of the puzzling and potentially contradictory results, offer some tentative explanations," perhaps especially in light of the five problems noted above "and propose an agenda for further research" intended in some measure to overcome some of these perceived problems. Only such future research will determine the extent to which these problems can be addressed by methodological advances within QEA, as opposed to being inherent in QEA itself.

More recently, Issue No. 2 of the 2014 H-Diplo | ISSF Forum [30] contains a vigorous exchange between contributors to what Scott Sagan [31] terms, in his Introduction, as two recent intellectual renaissances that have emerged in the field of nuclear security studies.[c] One of these has occurred in political science, much of it seeming associated to what we term here as QEA, and the other "occurring in history, as new archives have opened up and scholars are studying such important subjects as Cold War crises, the evolution of international institutions such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and the International Atomic Energy Agency (IAEA), and the history of medium powers and smaller states that decided to pursue or decided to stop pursing nuclear weapons." Sagan laments that these two evolutions "have largely developed in completely separate spheres, or on parallel tracks at best." The differing views expressed in this issue certainly attest to that, as well as perhaps serving as a first step toward providing synergies between these two heretofore distinct lines of intellectual development.

DECISIONS, DECISIONS
This section is intended as a simple illustration of possible synergism between QEA and rational models of the general type that formed the foundation for nuclear deterrence. The idea is that QEA could provide actual values for the otherwise only notional parameters of rational models. A nuclear-related field in which this already routinely is done is safety of nuclear reactors, in which empirical analysis of industry-wide failure data provides statistical estimates of failure rates [32], which then routinely are used as Bayesian priors subject to plant-specific updating to provide failure rates suitable for use in plant-specific probabilistic risk assessments.

Consider the following problem. The international community is contemplating intervention to prevent a rogue state from proliferating. The community assesses that the probability per unit time of the state proliferating is $\lambda > 0$. The consequences of a successful proliferation are C_P, measured on some scale, at the time at which the proliferation occurs. The consequences of an intervention, again at the time the intervention occurs, are C_I, measured on the same scale as the consequences of

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the proliferation. If all consequences are discounted to their present value at rate $\gamma \geq 0,$ then at what time should the international community intervene in order to minimize the expected net present value of the associated consequences?

This problem can be formulated [33] as a simple rational choice model, termed as the "dynamic intervention" game. The answer turns out to be that the optimal time of intervention is either never or immediately, according respectively as $C_P\lambda$ is less than or greater than $C_I(\lambda + \gamma)$, with a "thin" region of equality at which there is indifference as to the exact time of intervention.

Now λ is simply a hazard rate for proliferation, estimates of which could be obtained from QEA, e.g. following the approach of Singh and Way [8], as discussed above. Knowing that only the two choices of intervention time described above are sensible, at any given time one conceivably could classify any state as either "never intervene" or "intervene now," according respectively as its estimated hazard rate for proliferation falls below or exceeds some threshold value. One could then attempt to determine the optimal threshold value for intervention; that value would of course depend upon the costs of errors due to uncertainty in the proliferation (hazard) rate, which in turn depends upon the nature of the intervention contemplated.

CONCLUSIONS
A three-factor representation of the proliferation risk along a particular technological pathway gives an informative view of the role of proliferation resistance within proliferation risk. Elements of proliferation risk, as so revealed, can usefully be studied by quantitative empirical analysis of open-source datasets developed recently within the academic field of International Relations. This approach is best viewed as complementary and supplementary to more traditional methodologies. Integration between various such approaches is somewhat haltingly underway, fueled by vigorous discussions between devotees of the various methodologies. A simple example of possible such synergism is illustrated, in the form of use of proliferation rates from QEA to guide optimal timing of international intervention in suspected cases of proliferation attempts.

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AN ANALYSIS ON THE CORRELATES OF NUCLEAR PROLIFERATION

AND NUCLEAR ENERGY

A Proposal

by

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1. INTRODUCTION

The advent of the nuclear age brought with it both peaceful and non-peaceful nuclear applications. The spread of nuclear weapons technology began in the early stages of World War II. Currently, nine States have nuclear weapons and multiple other States possess the capabilities to start a nuclear weapons program. Only five States are recognized through the Nuclear Non-Proliferation Treaty (NPT); United States (1945), Russia (1949), United Kingdom (1952), France (1960), and China (1964). There are four other States that possess nuclear weapons: India (1974), Israel (N/A), North Korea (YYYY) and Pakistan (1998). [1] Additional States of interests include Iran, Libya, and Syria. Besides accounting for current nuclear weapons States, it is also important to recognize when States initiated a nuclear weapons program, even if it failed or ceased. There are thirteen cases identifying decisions to initiate a nuclear weapons programs dating back to 1975 or earlier. [2] Finally, it must be recognized that the threat of nuclear weapons proliferation is at an all time high with respect to the technical capabilities of States. However, various security protocols (such as the NPT and Comprehensive Nuclear Test Ban Treaty) and organizations (International Atomic Energy Agency) have curbed major potential threats.

The spread of nuclear weapons signaled the importance to globally emphasize nuclear security and non-proliferation. Currently, nuclear weapons proliferation is the focal point of security concerns. [3] Nuclear weapons proliferation can severely impact strategic planning and have security implications regionally and globally. [4] Thus, it has become increasingly important to study nuclear security and nuclear proliferation.

Varying literature suggests nuclear opportunity and willingness as keys to nuclear proliferation. Nuclear opportunity refers to a State's capabilities, while nuclear willingness refers to a State's motivations to proliferate. [5] Intent, or nuclear willingness, is important in evaluating the latency threat of a State. Coupling intent with capabilities can lead to insight on a State's nuclear program, as these two factors are interdependent for successful proliferation.

To begin assessing nuclear capabilities, an analysis of the nuclear fuel cycle must be performed. The nuclear fuel cycle consists of several stages leading to electricity production from power reactors. In the front end of the fuel cycle, Uranium *enrichment* is an integral part of electricity production. Spent Fuel *Reprocessing*, in the back end of the fuel cycle, is key to counteracting the waste produced from nuclear reactors. Both uranium enrichment and spent fuel reprocessing (to recover plutonium) are of significance, as both can be utilized to acquire weapons usable fissile material.

To better understand enrichment and reprocessing, it is necessary to understand how enrichment and reprocessing work. Natural uranium consists of about 0.72% ^{235}U and 99.28% ^{238}U. Nuclear energy production is a result of the splitting of ^{235}U nuclei, or fission. The nuclear reactor type can dictate the enrichment level of ^{235}U, ranging from 2% to about 20%. The enrichment process uses isotope separation methods that can increase the concentration of one isotope relative to others. Enrichment processes have evolved rather quickly; possession of an enrichment facility can greatly decrease breakout time, time required to acquire a weapon, for a state.

Reprocessing uses chemical separation methods developed to recover usable fuel (U or Pu) from irradiated nuclear fuel at the end of the fuel cycle including natural uranium fuel from CANDU reactors. There are numerous types of reprocessing methods such as Plutonium Uranium Redox Extraction (PUREX), Uranium Extraction

(UREX), and Thorium Extraction (THOREX). The PUREX process is advantageous for states considering proliferation, as it produces two separate streams of materials (U and Pu). [6] Therefore, it can be seen that peaceful applications of nuclear energy can shorten breakout time, thus increasing a State's capability to proliferate. [7]

To begin analysis on the correlates of nuclear proliferation and nuclear energy (the work proposed for this thesis), a statistical tool needs to be used. Previous work by Mike Mella, Corey Freeman, and others has identified Bayesian networks as useful predictive tools. [4] These networks are based upon Bayes' theorem, which is used to calculate conditional probabilities. To further asses Bayes' theorem, take the following two independent events, H and E. There is an initial probability, P(H), based on a prior belief about H. Using P(E) the revised probability of H is represented as P(H|E). Based on this a conditional probability, P(H|E) can be represented as:

$$P(H|E) = \frac{P(H \cap E)}{P(E)} \tag{1.1}$$

The previous equation determines the probability of H occurring because E occurred. If H and E are mutually exclusive, H and E can be flipped, then Eq. (1.1) can be rewritten:

$$P(E|H) = \frac{P(E \cap H)}{P(H)} \tag{1.2}$$

The probability of the intersection of these events are identical. Additionally, the probability of E is equal to probability of the intersection of H and E plus the probability of the complement of H (Hc) and E. [4] With some algebraic manipulation,

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the generic Bayes' theorem becomes:

$$P(H|E) = \frac{P(E|H)P(H)}{P(E|H)P(H) + P(E|Hc)P(Hc)}$$

(1.3)

The above theorem establishes the basis of Bayesian networks. Bayesian networks represent joint probability models among given variables. [8] Characteristics of such networks include:

- A set of variables identifying important factors,

- Direct dependencies between variables are represented by directed edges (links) between the corresponding nodes,

- Each variable has a finite set of mutually exclusive states, and

- Each variable A with parents $B_1, ..., B_n$, will have an corresponding conditional probability table. [9]
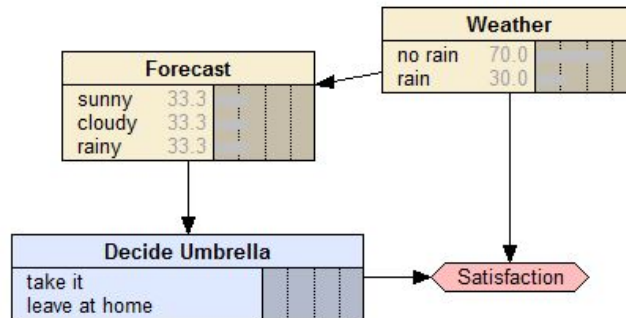

Figure 1.1: Example Bayesian Network

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An example network is shown above in Figure 1.1. This decision based network determines whether an umbrella is required based on the weather and forecast. These networks can represent relationships between predictive indicators making it a strong mechanism in comparison to other models, such as Naive Bayes and linear models. Bayesian networks are also powerful tools as they allow the incorporation of expert judgment. Expert judgment is heavily relied on in non-proliferation, to asses factors behind decisions to initiate a nuclear weapons program. For example, the Analysis of Competing Hypotheses (ACH) has been used more commonly in the intelligence analysis field. However, it is a non-computational method that requires an individual to identify links between various indicators and hypotheses. After which, the results are used to identify whether observed indicators support or refute each hypotheses. [10] An argument can be made to use Bayes networks in a similar fashion to ACH methods for analysts and policy makers to make decisions regarding proliferation.

2. OBJECTIVES

The objectives of this research are as follows:

1. Develop Bayesian network(s) that estimate the number of Enrichment and Reprocessing (ENR) facilities a state has at a specific point of time based on input parameters.

   (a) This network should reproduce historical examples and incorporate the potential to forecast (future predictions).

   (b) Develop multiple networks, by using different learning methods.

   (c) Validate network(s) for the following historical examples:

      i. Brazil,

      ii. India,

      iii. South Africa, and

      iv. Sweden.

2. Conduct an expert elicitation to better understand the role of differing indicators in the development of ENR facilities.

3. Conduct a sensitivity analysis on the network(s) developed.

   (a) Identify factors towards nuclear weapons proliferation and ensure they are modeled by the represented nodes.

   (b) Identify whether certain factors in nuclear weapons proliferation are dependent on one another. Ensure that dependence is shown in the network.

   (c) Determine the predicted effect of each node(s) on the dependent variable (predicting the number of ENR facilities).

(d) Smooth data by merging yearly data into sets of x(number) years. Determine the appropriate number of years to subset.

3. PROCEDURE

For the purpose of this study, "sensitive technologies" are intended to refer to Enrichment and Reprocessing facilities, but it will not be limited to these technologies. It is important to study the number of ENR facilities, as they can be indicators of the type of program developed (civil nuclear energy use versus weapons development).

Based on the literature review, the following factors will be considered as pertinent to developing ENR facilities [11]:

1. Technical Capability

    (a) GDP per Capita

    (b) Nuclear Weapons Arsenal (Binary)

    (c) Nuclear Electricity Production

2. Motivation

    (a) Super Power Alliance (Binary)

    (b) Number of Disputes

    (c) Number of ENR Facilities by Rival States

3. Number of ENR Facilities by Trading Partners

The predictive network(s) developed will be simulated through Bayesian networks. Bayesian analysis is used in cases where courses of actions are chosen involving tradeoffs between multiple objectives. [12] The factors identified above will drive the system in estimating the dependent variable.

4. SIGNIFICANCE OF WORK

Heightened global interest in nuclear security and non-proliferation marks the significance of such relevant studies. This project focuses on recognizing the factors that affect nuclear proliferation by studying and validating historical examples. Bayesian networks will be developed for validation of these historical examples. The developed model will also attempt to forecast potential situations. This should establish the models potential as a policy analysis tool.

This thesis will provide a quantitative and mathematically defensible position on the correlates of nuclear proliferation.

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